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Specification and Drawings, as originally filed, with Application for Patent Serial No: **2,423,445,** on March 26, 2003, by **Z-TECH (CANADA) INC.**, assignee of Adam Semlyen and Milan Graovac, for "Diagnosis of Disease by Determination of Electrical Properties of a Body Part".

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ABSTRACT OF THE DISCLOSURE

A system and method for diagnosing the possibility of disease in a body part is described. The system includes an electrical data unit for measuring electrical data of the body part, the electrical data unit having a plurality of N_e electrodes. The system also includes a network module for representing the body part by a network, the network having external nodes and internal nodes connected by current pathways. The system further includes an electrical properties module for determining electrical properties of the pathways using the measured electrical data, and a diagnosis module for utilizing the electrical properties to diagnose the possibility of disease in the body part.

Diagnosis of Disease by Determination of Electrical Properties of a Body Part

Field of the invention

This invention relates to medical diagnosis of disease and specifically relates to diagnosis of disease by measuring electrical properties of a part of the body.

Background of the invention

Measurement devices of various kinds have been used to diagnose disease. For example, x-ray machines measure tissue x-ray density, ultrasound machine measure acoustic density, and thermal sensors measure differences in tissue heat generation and conduction, which measurements have diagnostic value. In addition to these devices, there exist devices that can measure electrical data, such as voltage or impedance, of a body part for the purpose of diagnosing disease, such as breast cancer.

Voltage and impedance values of various types of body tissue are well known through *in vivo* studies on humans or from excised tissue made available following therapeutic surgical procedures. It is well documented that a decrease in electrical impedance occurs in tissue as it undergoes cancerous changes. This finding is consistent over many animal species and tissue types, including, for example, human breast cancers.

However, even though this relationship between impedance and cancer is well known, it is difficult to make straightforward absolute comparisons between individuals. For example, if a patient has a smaller breast impedance than that of an average female, this does not imply that the patient has breast cancer because several factors could give rise to such a smaller value that are unrelated to cancer. For example, it is known that voltage or impedance is related to the percent fat content in an individual. Obese women, for instance, would be expected to have breast impedance values that are significantly different than average.

Despite such difficulties, a method that permits comparisons of electrical properties for diagnostic purposes has been developed that involves homologous body parts, i.e., body parts that are substantially similar, such as a left breast and a right breast. In this method, the impedance of a body part of a patient is compared to the impedance of the homologous body part of the *same* patient.

One technique for screening and diagnosing diseased states within the body using electrical impedance is disclosed in U.S. Pat. No. 6,122,544, which is incorporated herein by reference. In this patent, data are obtained from two anatomically homologous body regions, one of which may be affected by disease. Differences in the electrical properties of the two

homologous body parts could signal disease. One body part, assumed to be healthy, is used as a baseline with which to evaluate the homologous body part for disease.

To perform such an evaluation of the body part for disease, a current is injected between an electrode pair and the resultant voltage is measured therebetween. This voltage is indicative of the impedance of the body part and may have diagnostic value.

However convenient this method is, obtaining impedance in this manner is simplistic. When current is injected, the flow of electricity through the body part is expected to take one or more complex, jagged paths from the starting electrode to the final electrode. The conventional approach does not account for the internal current pathways that the electricity follows.

Summary of the invention

The present invention describes a system and method for calculating the resistive properties of a body part in a way that accounts for the internal topology of current pathways. By accounting for this topology, a more reliable diagnosis of disease can be achieved.

In particular, a system for diagnosing the possibility of disease in a body part is described herein. The system includes an electrical data unit for measuring electrical data of the body part, the electrical data unit having a plurality of N_e electrodes. The system further includes a network module for representing the body part by a network, the network having external nodes corresponding to the location of the plurality of the N_e electrodes and internal nodes. The internal and external nodes are connected by current pathways. The system also includes an electrical properties module for determining electrical properties of the pathways using the measured electrical data, and a diagnosis module for utilizing the electrical properties to diagnose the possibility of disease in the body part.

For example, the electrical properties module can determine the resistance of each of the current pathways, thereby obtaining a conductance matrix. The electrical properties module can likewise repeat these steps to obtain the conductance matrix of a homologous body part. For instance, the conductance matrices of the left and right breast can be obtained and then compared by the diagnosis module to diagnose disease.

Also described herein is a corresponding method for diagnosing the possibility of disease in a body part. The method includes measuring electrical data of the body part with a plurality of N_e electrodes, and representing the body part by a network. The network has external nodes corresponding to the location of the plurality of the N_e electrodes and internal

nodes, the internal and external nodes being connected by current pathways. The method also includes determining electrical properties of the pathways using the measured electrical data, and utilizing the electrical properties to diagnose the possibility of disease in the body part.

Brief description of the drawings

Figure 1 is a block diagram of the diagnostic system of the present invention;

Figure 2 is a network of nodes and current pathways, according to one embodiment of the present invention;

Figure 3 is a block diagram of the electrical data unit of the diagnostic system of Figure 1;

Figure 4 is a block diagram of the electrical properties module of the diagnostic system of Figure 1;

Figure 5 is a block diagram of the diagnosis module of the diagnostic system of Figure 1;

Figure 6 is a block diagram of the admittance module of the electrical data unit of Figure 3; and

Figure 7 is a block diagram of the conductance module of the electrical properties module of Figure 4.

Detailed description of the invention

Figure 1 shows a diagnostic system 10 for diagnosing the possibility of disease in a body part, such as cancer of the breast. System 10 includes an electrical data unit 12 having a plurality of N_e electrodes 14, a network module 16, an electrical properties module 18, and a diagnosis module 20.

Electrical data unit 12 measures electrical data of the body part using the N_e electrodes 14. The N_e electrodes 14 includes electrodes for injecting current into the body part, and electrodes for measuring resultant voltages. In one embodiment, the current injection electrodes and the voltage measurement electrodes coincide. An electrode array containing a plurality of electrodes similar to one suitable for use in the present invention is disclosed in U.S. Patent No. 6,122,544.

The electrode array can be connected to a multichannel device that is coupled to electrodes 14. A central control unit, consisting of a central processing unit (CPU) and RAM and ROM memories, selects, in rapid

succession, sets of electrodes for current injection and voltage measurement. One or more analog-to-digital (A/D) converters can convert the analog measurements to a digitized form. Digital data from the A/D converter are processed by the CPU, where they undergo real time analyses for error checking, routing to a monitor for display of raw or processed data, as well as storage in memory for further analysis and output to the monitor and a printer.

Network module 16 includes hardware and/or software for representing the body part by a network. The network has external nodes corresponding to the location of the plurality of the N_e electrodes 14 and internal nodes. The internal and external nodes are connected by current pathways through which current flows. The external nodes lie on the perimeter of the network, while the internal nodes lie inside. A description of the network appears below in connection with Figure 2.

The electrical properties module 18 includes software and/or hardware for determining electrical properties of the current pathways using the measured electrical data. For example, the electrical properties module 18 can use the electrical data obtained by the electrical data unit 12 to find the resistances of each of the current pathways in the network. The resistances of the current pathways can be arranged as a conductance matrix.

Diagnosis module 20 utilizes the determined electrical properties of the pathways to diagnose the possibility of disease in the body part. For

example, diagnosis module 20 can compare the conductance matrix of the body part to an average matrix obtained from a population group, or to a conductance matrix obtained from a homologous body part, as described in more detail below.

Figure 2 shows one possible network 50 of nodes and current pathways, according to one embodiment of the present invention. The network 50 includes eight external nodes 52, four internal nodes 54 and twenty-four pathways 56. The electrical data unit 12 injects current between two electrodes and then measures the resultant voltage between two electrodes that need not coincide with the two electrodes used to inject the current. The electrodes for injecting current and for measuring voltage lie on the external nodes 52.

Electrical properties module 18 then calculates electrical properties, such as the conductance of the pathways 56. Network 50 represents the body part and the pathways represent possible paths that current travels when injected into the body part. By using such a network, a more complete description can be obtained of the conductance properties of the body part as compared to a network in which no internal nodes are included. In the example of Figure 2, the current pathways are line segments that intersect only at external nodes or internal nodes.

Figure 3 shows the electrical data unit 12 of Figure 1. Electrical data unit 12 includes an impedance module 22 and an admittance module 24. The electrical data unit 12 can also include an averaging module 25. In circuit theory, the impedance Z is a complex number, whose real part is the resistance R and whose imaginary part is the capacitive reactance X_c. The magnitude of Z is given by V/I, where V and I are the amplitudes of the voltage and current, respectively. Both the resistance and reactance can be measured, and analyzed in the present invention.

Impedance module 22 obtains an impedance z_{ij} of the body part as follows. The electrical data unit injects a current I_i between an ith electrode, chosen from the N_e electrodes 14, and a reference electrode. For simplicity, and without loss of generality, the reference electrode is taken to be the N_eth electrode of the N_e electrodes 14. The electrical data unit 12 measures a resultant voltage V_j between a jth electrode chosen from the plurality of electrodes 14 and the reference N_eth electrode. The impedance module 22 calculates z_{ij} according to $z_{ij} = V_i / I_j$ where $1 \le i \le N_e - 1$ and $1 \le j \le N_e - 1$. The electrical data unit 12 repeats the step of injecting and the step of measuring with varying electrodes to build an $N_e - 1 \times N_e - 1$ impedance matrix Z with matrix elements z_{mn} given by

$$z_{mn} = V_m / I_n \qquad (1)$$

where $1 \le m \le N_e - 1$ and $1 \le n \le N_e - 1$. As described in more detail below, the admittance module 24 calculates an $N_e - 1 \times N_e - 1$ admittance matrix Y from the impedance matrix Z.

The averaging module 25 calculates an average admittance matrix, $\overline{Y}$. In one embodiment, the electrical properties module 18 uses $\overline{Y}$ to calculate the conductance matrix.

Figure 4 shows the electrical properties module 18 of Figure 1. The electrical properties module 18 includes a conductance module 26 for determining a conductance matrix, G, for the body part by using the admittance matrix Y. The conductance matrix characterizes the conductance properties of the body part. Because the presence of some diseases, such as cancer, is known to alter the conductance of a body part, the conductance matrix possesses considerable diagnostic value.

Figure 5 shows the diagnosis module 20 of Figure 1. The diagnosis module 20 includes a comparator 28 for comparing the conductance matrix for the body part to an average conductance matrix from a population group to diagnose the possibility of disease in the body part. A difference between the two matrices could indicate the presence of disease. Alternatively, or in addition, the comparator 28 can compare the conductance matrix for the body part, such as a left breast, to a conductance matrix for a homologous body

part, the right breast. Again, a difference between the two matrices could indicate the presence of disease.

Figure 6 shows the admittance module 24 of Figure 3. The admittance module 24 includes an auxiliary module 30 and an admittance matrix calculator 32.

The auxiliary module 30 calculates an $N_e - 1 \times N_e - 1$ auxiliary matrix A with matrix elements a_{ij}. The auxiliary matrix A is self-adjoint by construction and is given by

$$A = \left(Z^{-1} + \operatorname{adj} Z^{-1}\right)/2 \tag{2}$$

where adj denotes the adjoint.

The admittance matrix calculator 32 calculates the $N_e \times N_e$ admittance matrix, having matrix elements y_{ij}, according to

$$y_{ij} = \begin{cases} a_{ij} \text{ if } 1 \le i \le N_e - 1 \text{ and } 1 \le j \le N_e - 1 \\ x_i \text{ if } i = N_e \text{ or } j = N_e \\ -\sum_{n=1}^{N_e - 1} x_n \text{ if } i = N_e \text{ and } j = N_e \end{cases} \tag{3}$$

where

$$x_j = \sum_{n=1}^{N_e - 1} a_{jl}. \tag{4}$$

The admittance equation satisfies

$$Yv_e = i_e. \tag{5}$$

where v_e is the vector of external node potentials whose elements are the V_m defined above, and i_e is the vector of external currents whose elements are the I_n defined above. In what follows, internal current vectors i_i are taken to be zero, i.e., current is only injected at the external nodes.

Figure 7 shows the conductance module 26 of Figure 4. The conductance module includes a conductance matrix calculator 34. The conductance matrix calculator 34 obtains the conductance matrix, G, using the admittance matrix by solving the conductance equation

$$G_{ee} - G_{ei} G_{ii}^{-1} G_{ei}^{T} = \mathrm{Re}(Y) \qquad (6)$$

where, if N_e is the number of external nodes and N_i is the number of internal nodes, then G_{ee} is an $N_e \times N_e$ matrix, G_{ei} is an $N_e \times N_i$ matrix and G_{ii} is an $N_i \times N_i$ matrix defined by

$$G = \begin{pmatrix} G_{ee} & G_{ei} \\ G_{ei}^{T} & G_{ii} \end{pmatrix}. \qquad (7)$$

The equation $G_{ee} - G_{ei} G_{ii}^{-1} G_{ei}^{T} = \mathrm{Re}(Y)$ is obtained from the standard nodal equation

$$G\begin{pmatrix} v_e \\ v_i \end{pmatrix} = \begin{pmatrix} i_e \\ i_i = 0 \end{pmatrix}$$

by eliminating the vector of internal potentials, v_i, from the nodal equation using $v_i = -G_{ii}^{-1} G_{ei}^{T} v_e$, and then substituting $Y v_e = i_e$.

Alternatively, the conductance matrix calculator 34 obtains the conductance matrix by solving the conductance equation

$$G_{ee} - G_{ei}G_{ii}^{-1}G_{ei}^{T} = \mathrm{Re}(\overline{Y}) \quad (8)$$

where the averaging module 25 calculates an average impedance matrix $\overline{Y}$ by averaging over one or more impedance matrices, including Y, obtained by varying the reference electrode chosen from among the plurality of electrodes 14.

The conductance matrix calculator 34 can solve Equation (6) or (8) using several methods. Two methods, Newton's method for a system of nonlinear equations and a continuation method are now described in detail.

Solution of Conductance Equation:

The general form of the conductance equation (Eq. 6 or 8) is

$$f(g) = (G_{ee} - G_{ei}G_{ii}^{-1}G_{ei}^{T}) - G_{m} = 0 \quad (9)$$

where *f(g)* is a function of elements of *GG*, where *g* is a vector

$$g = \begin{bmatrix} g_{ee} \\ g_{ei} \\ g_{ie} \\ g_{ii} \end{bmatrix}$$

$$g_{ee} = \begin{bmatrix} G_{ee}(:,1) \\ \vdots \\ G_{ee}(:,N_e) \end{bmatrix}, \quad g_{ie} = \begin{bmatrix} G_{ei}^T(:,1) \\ \vdots \\ G_{ei}^T(:,N_e) \end{bmatrix}, \qquad \text{(9a)}$$
$$g_{ei} = \begin{bmatrix} G_{ei}(:,1) \\ \vdots \\ G_{ei}(:,N_e) \end{bmatrix}, \quad g_{ii} = \begin{bmatrix} G_{ii}(:,1) \\ \vdots \\ G_{ii}(:,N_i) \end{bmatrix}$$

(A) *Newton's Method for a system of nonlinear equations*

Let $g = [g_i]$, $i = 1,\dots,N \times N$, be a column vector of all possible pathways for given *N*. Let g_0 be a vector of estimated elements of *GG* for the given network. Vector g has zero for each $g(i)$ that corresponds to certain $GG(p,q)$ and nodes *p* and *q* are not connected. The Jacobian is $J(g) = \frac{\partial f}{\partial g}$. Substituting g_0 in (9), $f(g_0) \neq 0$ is calculated.

A new vector $g^{(n)}$ is calculated from:

$$\begin{aligned} J(g^{(n)})\Delta g^{(n)} &= -f(g^{(n)}) \\ g^{(n+1)} &= g^{(n)} + \Delta g^{(n)} \end{aligned} \qquad \text{(10)}$$

For g_0 close enough to g^* (solution of the problem (9)), the iterative method described by equations (10) quadratically converges to g^*. If g_0 is not a good initial guess for g^*, system (10) may not converge. In that case, the continuation method described below is applied. If the number of equations is greater than the number of unknowns, a least squares problem is being solved using the Gauss-Newton method. In that case, the convergence is not quadratic.

(B) *Continuation Method*

For a function $f: R^n \rightarrow R^m$, a numerical method, sensitive to the initial guess, can be used to solve the equation $f(g)=0$, where $g \in R^n$. If the guess is not sufficiently close to the solution g^*, the numerical method might not converge. To obtain a sufficiently close initial vector $g^{(0)}$ for problem $f(g)=0$, an augmented function $\bar{\bar{f}}(g(\theta),\theta): R^{n+1} \rightarrow R^m$ can be considered that is defined as:

$$\bar{\bar{f}}(g(\theta),\theta)=(1-\theta)\bar{f}(g(\theta))+\theta f(g(\theta)), \tag{11}$$

and the following equivalent problem solved:

$$\bar{\bar{f}}(g(\theta),\theta)=0, \quad \theta \in [0,1] \tag{11a}$$

where:

$\bar{f}(g): R^n \to R^m$ is a function of g, such that equation $\bar{f}(g)=0$ is easy to solve, and θ is a real number.

The important properties of the new function are:

$$\bar{\bar{f}}(g(\theta),\theta)=\begin{cases} \bar{f}(g), & \theta=0 \\ (1-\theta)\bar{f}(g)+\theta f(g), & \theta\in\,]0,1[\\ f(g), & \theta=1 \end{cases}$$

For $\theta=0$, the equation (11a) becomes $\bar{f}(g)=0$, which is easy to solve by construction.

For $\theta=1$, the problem (11a) is identical to the original problem $f(g)=0$. For $\theta\in]0,1[$, the problem (11a) becomes

$$(1-\theta)\bar{f}(g(\theta))+\theta f(g(\theta))=0$$

The following method takes the solution of the problem $g=0$ as the initial guess $g^{(0)}$ for the close problem $(1-\theta)g(\theta)+\theta f(g(\theta))=0$, where is $\theta=0+\delta\theta$, and $\delta\theta \ll 1$. The underlying assumption is that the solution for the problem $\bar{\bar{f}}(g(\theta),\theta)$ is close enough to $g^{*}(\theta+\delta\theta)$ for the problem $\bar{\bar{f}}(g(\theta+\delta\theta),\theta+\delta\theta)$ so that the numerical algorithm converges to $g^{*}(\theta+\delta\theta)$.

To summarize, the continuation method includes a) solving the problem $\bar{f}(g(\theta),\theta)=0$ for $\theta=0$, b) taking the solution $g^*(\theta)$ as the initial guess $g^{(0)}(\theta+\delta\theta)$ for

$$\bar{f}(g(\theta+\delta\theta),\theta+\delta\theta)=(1-(\theta+\delta\theta))\tilde{f}(g(\theta+\delta\theta))+(\theta+\delta\theta)f(g(\theta+\delta\theta)),$$

where $\delta\theta$ is a small step, c) attempting to solve this problem using a Gauss-Newton algorithm, d) if the Gauss-Newton algorithm converges, setting $\theta=\theta+\delta\theta$, $\delta\theta=\alpha\cdot\delta\theta$, where $\alpha>1$ is the acceleration coefficient, and if it does not converge, setting $\delta\theta=\delta\theta/2$, and e) repeating step b) until $\theta=1$.

These methods can be used to solve the conductance equation:

$$f(g)=(G_{ee}-G_{el}G_{ll}^{-1}G_{el}^T)-G_m$$

The matrix of finite differences is $\Delta f=[\Delta f_1 \quad \Delta f_2 \quad \cdots \quad \Delta f_{Ne}]$, where

$$f_k(g)=(g_{eek}-G_{el}G_{ll}^{-1}g_{lek})-g_{mk}, \qquad k=1...Ne.$$

From the above equation,

$$\Delta f_k=\Delta g_{eek}-\Delta G_{el}G_{ll}^{-1}g_{lek}-G_{ei}\Delta G_{ll}^{-1}g_{lek}-G_{el}G_{ll}^{-1}\Delta g_{lek} \qquad (14)$$

Matrix ΔG_{ll}^{-1} can be calculated from the equation $G_{ll}^{-1}G_{ll}=I$ as follows

$$G_{ll}^{-1}G_{ll}=I \qquad |\Delta$$

$$\Delta G_{ll}^{-1}G_{ll}+G_{ll}^{-1}\Delta G_{ll}=0 \qquad |\cdot G_{ll}^{-1}$$

$$\Delta G_{ii}^{-1} = -G_{ii}^{-1} \Delta G_{ii} G_{ii}^{-1} \tag{15}$$

Substituting (15) in (14) leads to:

$$\Delta f_k = \Delta g_{eek} - \Delta G_{ei}(G_{ii}^{-1} g_{iek}) + (G_{ei} G_{ii}^{-1}) \Delta G_{ii} (G_{ii}^{-1} g_{iek}) - (G_{ei} G_{ii}^{-1}) \Delta g_{iek} \tag{16}$$

The next step is to reorder the matrix products in (16). Each ΔG_{**} should come as a vector Δg_{**} to the right hand side of the corresponding matrix product. Δg_{**} is a column vector of all columns of ΔG_{**} as indicated by (9a). By applying the rule

$$\Delta XB \iff A \Delta x \tag{17}$$

Equation (16) becomes

$$\Delta f_k = \Delta g_{eek} - M_{1k} \Delta g_{ei} + M_{2k} \Delta g_{ii} - M_3 \Delta g_{iek} \tag{17a}$$

where $M_3 = G_{ei} G_{ii}^{-1}$, $M_{2k} = G_{ei} G_{ii}^{-1} A_k$, and M_{1k} and A_k are calculated by applying (17):

$$\begin{aligned} \Delta G_{ei}(G_{ii}^{-1} g_{iek}) &= M_{1k} \Delta g_{ei} \\ \Delta G_{ii}(G_{ii}^{-1} g_{iek}) &= A_k \Delta g_{ii} \end{aligned}$$

Equation (17a) can be written as:

$$\Delta f_k = [I \quad -M_{1k} \quad M_{2k} \quad -M_3] \cdot \begin{bmatrix} \Delta g_{eek} \\ \Delta g_{ei} \\ \Delta g_{ii} \\ \Delta g_{iek} \end{bmatrix} \tag{18}$$

where $J_k = [I \quad -M_{1k} \quad M_{2k} \quad -M_3]$ is the Jacobian matrix corresponding to the k^{th} column of $F(g^{(k)})$ in equation (10).

Solving the system

$$J_k^{(n)} \cdot \begin{bmatrix} \Delta g_{cek}^{(n)} \\ \Delta g_{cl}^{(n)} \\ \Delta g_{ll}^{(n)} \\ \Delta g_{lsk}^{(n)} \end{bmatrix} = -f_k^{(n)}, \quad k = 1,\ldots,Ne$$

is equivalent to solving equation (19).

$$\left[\begin{array}{ccc|c|c|ccc} I & & 0 & -M_{11}^{(n)} & M_{21}^{(n)} & -M_3^{(n)} & & 0 \\ & I & & -M_{12}^{(n)} & M_{22(n)} & & -M_3^{(n)} & \\ & & \ddots & \vdots & \vdots & & & \ddots \\ 0 & & I & -M_{1Ne}^{(n)} & M_{2Ne}^{(n)} & 0 & & -M_3^{(n)} \end{array}\right] \cdot \begin{bmatrix} \Delta g_{ce}^{(n)} \\ \Delta g_{cl}^{(n)} \\ \Delta g_{ll}^{(n)} \\ \Delta g_{ls}^{(n)} \end{bmatrix} = -\begin{bmatrix} \Delta f_1^{(n)} \\ \Delta f_2^{(n)} \\ \vdots \\ \Delta f_{Ne}^{(n)} \end{bmatrix} \tag{19}$$

To simplify equation (19), the vector of admittances may be written as

$$gg = T_r \cdot g_{branch} \tag{20}$$

where

$$gg = \begin{bmatrix} g_{ce} \\ g_{cl} \\ g_{ll} \\ g_{ls} \end{bmatrix},$$

g_{branch} is a vector of the current pathways in the selected network whose dimension is ($Nb \times 1$), T_r is a matrix defined by the network so that equation (20) holds:

$$T_r(i,j) = \begin{cases} 1 & g_{branch}(j) \equiv gg(i) \\ 0 & \text{otherwise} \end{cases}$$

The dimension of the matrix T_r is $(Ne + Ni)^2 \times Nb$.

Substituting (20) in (19) results in a reduced system (21): it has the same number of equations, but only Nb unknowns and lower rank of reduced Jacobian J_r:

$$J_r^{(n)} \cdot \Delta g_{branch}^{(n)} = -\begin{bmatrix} \Delta f_1^{(n)} \\ \Delta f_2^{(n)} \\ \vdots \\ \Delta f_{Ne}^{(n)} \end{bmatrix} \qquad (21)$$

where

$$J_r = \left[\begin{array}{ccc|c|c|cccc} I & & 0 & -M_{11}^{(n)} & M_{21}^{(n)} & -M_3^{(n)} & & & 0 \\ & I & & -M_{12}^{(n)} & M_{22(n)} & & -M_3^{(n)} & & \\ & & \ddots & \vdots & \vdots & & & \ddots & \\ 0 & & I & -M_{1Ne}^{(n)} & M_{2Ne}^{(n)} & 0 & & & -M_3^{(n)} \end{array}\right] \cdot T_r$$

and Δg_{branch} is a vector of current pathways admittance corrections (of size Nb). The new admittance vector $g_{branch}^{(n+1)}$ is calculated from the equation

$$g_{branch}^{(n+1)} = g_{branch}^{(n)} + \Delta g_{branch}^{(n)} \qquad (22)$$

Similar to (20), vector $g^{(n+1)}$ can be calculated from $g_{branch}^{(n+1)}$ as

$$g^{(n+1)} = T \cdot g_{branch}^{(n+1)} \qquad (23)$$

where T is a matrix defined by the chosen network so that the equation (23) holds:

$$T(i,j) = \begin{cases} 1 & g_{branch}(j) \equiv g(i) \\ 0 & \text{otherwise} \end{cases}$$

The dimension of the matrix T is $((Ne+Ni)^2 \times Nb)$.

There are other methods, besides the method just described, which can be used by the conductance matrix calculator 34 for obtaining the conductance matrix. For example, the nodal equation introduced above, together with Eq. 5 yields

$$\begin{aligned} G_m &= G_{ee} + G_{ei} v_i \\ 0 &= G_{ie} + G_{ii} v_i \end{aligned} \qquad (24)$$

where $G_m \equiv \mathrm{Re}(Y)$. In Equations (24), G_m is the measured (i.e. specified) conductance matrix and v_e does not appear because it is set to the identity matrix. In the previous method for obtaining the conductance matrix, $G_{ie} + G_{ii} v_i$ was forced to be zero because the internal nodes are not connected to the outside, resulting in Eq. 8.

Equations (24), however, may be solved directly by noting that the '0' could be viewed as a measured '0_m' meaning that it is subject to errors similar

to those of G_m. This changes the internal nodes from unobservable to observable leading to a well-conditioned problem.

Linearization of Equations (24) gives

$$\begin{aligned} \Delta G_m &= \Delta G_{ee} + \Delta G_{ei} v_i + G_{ei} \Delta v_i \\ \Delta 0_m &= \Delta G_{ie} + \Delta G_{ii} v_i + G_{ii} \Delta v_i \end{aligned} \tag{25}$$

Among the incremental variables, Δv_i appears and is part of the solution, although not of primary interest. The left side of Equations (25) represents an extended set of mismatches ($\Delta 0_m$ being part).

Equations (24) may also be solved without linearization by alternatively and iteratively solving for the elements in G (with V_i being a constant) and V_i (with the elements of G being held at a fixed value).

A note about the dimensions of Equations (24) is in order. G_m is actually obtained by a set of measurements (as many independent measurements as there are columns) and for each of these the outside voltage is applied to one electrode (plus the base) only. If it is assumed that all voltages are given in a per-unit system then the external voltage matrix v_e may be a unity matrix, hence v_e does not appear in the Equations 24.

Taking note of Equation (8), if v_e contains multiple measurements arranged so that there is a current only between one electrode and the base electrode:

$$v_e = I v_{base}$$

where I is the identity matrix. If the system is linear, division by the base voltage can be performed and all voltages calculated subsequently are expressed with respect to v_{base}. In this case, the equations

$$\begin{aligned} i_e &= G_m v_e = G_{ee} v_e + G_{ei} v_i \\ 0 &= G_{ie} v_e + G_{ii} v_i \end{aligned}$$

can be re-written as Equations (24).

Once the conductance matrix calculator 34 finds the conductance matrix for the body part, using any of the methods described above, the aforementioned steps can be repeated to obtain the conductance matrix of the homologous body part. The diagnosis module 20 can then compare the conductance matrix for the body part and the conductance matrix for the homologous body part by using several comparison methods. For example, the norm of the difference of these two matrices can be computed, and if it is greater than some threshold, then further analysis can be performed as this difference may signal the presence of disease.

Several computer systems can be used to implement the method for diagnosing disease in a body part. The computer system can include a monitor for displaying parts or the whole conductance matrix, or for displaying the difference between the conductance matrix for the body part and the conductance matrix for the homologous body part using one of several visual

methods. In one embodiment, the method can be implemented on a 2 GHz Pentium™ 4 system with 512 MB RAM.

It should be understood that various modifications could be made to the embodiments described and illustrated herein, without departing from the present invention, the scope of which is defined in the appended claims. For example, although emphasis has been placed on describing a system for diagnosing breast cancer, the principles of the present invention can also be advantageously applied to other diseases of other body parts.

Claims

What is claimed is:

1. A method for diagnosing the possibility of disease in a body part, the method comprising

measuring electrical data of the body part with a plurality of N_e electrodes;

representing the body part by a network, said network having external nodes corresponding to the location of the plurality of the N_e electrodes and internal nodes, wherein the internal and external nodes are connected by current pathways;

determining electrical properties of the pathways using the measured electrical data; and

utilizing the electrical properties to diagnose the possibility of disease in the body part.

2. The method of claim 1, wherein the step of measuring includes measuring an impedance z_{ij} of the body part.

3. The method of claim 2, wherein the step of measuring an impedance z_{ij} of the body part includes

injecting a current I_i between an i^{th} electrode chosen from among the plurality and a reference electrode taken to be the N_e electrode of the plurality;

measuring a resultant voltage V_j between a j^{th} electrode chosen from among the plurality and the reference N_e^{th} electrode; and

repeating the steps of injecting and measuring to calculate an $N_e-1 \times N_e-1$ impedance matrix Z with matrix elements z_{mn} given by $z_{mn} = V_m / I_n$ where $1 \leq i \leq N_e - 1$ and $1 \leq j \leq N_e - 1$.

4. The method of claim 3, wherein the step of measuring electrical data includes calculating an $N_e-1 \times N_e-1$ admittance matrix Y from the impedance matrix Z.

5. The method of claim 4, wherein the step of determining electrical properties of the pathways includes determining a conductance matrix, G, for the body part by using the admittance matrix.

6. The method of claim 5, wherein the step of utilizing the electrical properties includes

obtaining an average conductance matrix from a population group; and

comparing the conductance matrix for the body part and the average conductance matrix from a population group to diagnose the possibility of disease in the body part.

7. The method of claim 5, wherein the step of utilizing the electrical properties includes

determining a conductance matrix for a homologous body part; and

comparing the conductance matrix for the body part and the conductance matrix for the homologous body part to diagnose the possibility of disease in the body part.

8. The method of claim 5, wherein the step of calculating an $N_e - 1 \times N_e - 1$ admittance matrix Y includes

calculating an $N_e - 1 \times N_e - 1$ auxiliary matrix A with matrix elements a_{ij}, the auxiliary matrix given by

$$A = \left(Z^{-1} + \operatorname{adj} Z^{-1}\right)/2;$$

calculating the admittance matrix Y, with matrix elements y_{ij}, according to

$$y_{ij} = \begin{cases} a_{ij} \text{ if } 1 \le i \le N_e - 1 \text{ and } 1 \le j \le N_e - 1 \\ x_i \text{ if } i = N_e \text{ or } j = N_e \\ -\sum_{n=1}^{N_e - 1} x_n \text{ if } i = N_e \text{ and } j = N_e \end{cases}$$

where

$$x_j = \sum_{n=1}^{N_e - 1} a_{jl}.$$

9. The method of claim 8, wherein the step of determining a conductance matrix includes solving the equation

$$G_{ee} - G_{el} G_{ll}^{-1} G_{el}^{T} = \mathrm{Re}(Y)$$

where, if N_e is the number of external nodes and N_i is the number of internal nodes, then G_{ee} is an $N_e \times N_e$ matrix, G_{ei} is an $N_e \times N_i$ matrix and G_{ii} is an $N_i \times N_i$ matrix defined by

$$G = \begin{pmatrix} G_{ee} & G_{ei} \\ G_{ei}^T & G_{ii} \end{pmatrix}.$$

10. The method of claim 9, wherein solving the equation includes utilizing at least one of Newton's method for a system of nonlinear equations and a continuation method.

11. The method of claim 8, wherein the step of measuring electrical data further includes calculating an average impedance matrix $\overline{Y}$, by averaging over one or more impedance matrices, including Y, obtained by varying the reference electrode chosen from among the plurality and analogously repeating the above steps.

12. The method of claim 11, wherein the step of determining a conductance matrix includes solving the equation

$$G_{ee} - G_{ei} G_{ii}^{-1} G_{ei}^T = \mathrm{Re}(\overline{Y}),$$

where, if N_e is the number of external nodes and N_i is the number of internal nodes, then G_{ee} is an $N_e \times N_e$ matrix, G_{ei} is an $N_e \times N_i$ matrix and G_{ii} is an $N_i \times N_i$ matrix defined by

$$G=\begin{pmatrix} G_{ee} & G_{ei} \\ G_{ei}^{T} & G_{ii} \end{pmatrix}.$$

13. The method of claim 12, wherein solving the equation includes utilizing at least one of Newton's method for a system of nonlinear equations and a continuation method.

14. The method of claim 1, wherein the current pathways intersect only at external nodes or internal nodes.

15. The method of claim 1, wherein the current pathways are line segments.

16. The method of claim 1, wherein the external nodes lie on a perimeter of the network and the internal nodes lie inside the perimeter.

17. A system for diagnosing the possibility of disease in a body part, the system comprising

an electrical data unit for measuring electrical data of the body part, said electrical data unit having a plurality of N_e electrodes;

a network module for representing the body part by a network, said network having external nodes corresponding to the location of the plurality of the N_e electrodes and internal nodes, wherein the internal and external nodes are connected by current pathways;

an electrical properties module for determining electrical properties of the pathways using the measured electrical data; and

a diagnosis module for utilizing the electrical properties to diagnose the possibility of disease in the body part.

18. The system of claim 17, wherein the electrical data unit includes an impedance module for obtaining an impedance z_{ij} of the body part.

19. The system of claim 18, wherein, after the electrical data unit a) injects a current I_i between an i^{th} electrode chosen from among the plurality and a reference electrode taken to be the N_e^{th} electrode of the plurality, and b) measures a resultant voltage V_j between a j^{th} electrode chosen from among the plurality and the reference N_e^{th} electrode, the impedance module calculates z_{ij} according to $z_{ij} = V_i / I_j$ where $1 \le i \le N_e - 1$ and $1 \le j \le N_e - 1$.

20. The system of claim 19, wherein, after the electrical data unit repeats the step a) of injecting and the step b) of measuring with varying electrodes, the impedance module calculates an $N_e - 1 \times N_e - 1$ impedance matrix Z with matrix elements z_{mn} given by $z_{mn} = V_m / I_n$ where $1 \le i \le N_e - 1$ and $1 \le j \le N_e - 1$.

21. The system of claim 20, wherein the electrical data unit further includes an admittance module for calculating an $N_e - 1 \times N_e - 1$ admittance matrix Y from the impedance matrix Z.

22. The system of claim 21 wherein the electrical properties module includes a conductance module for determining a conductance matrix, G, for the body part by using the admittance matrix.

23. The system of claim 22, wherein the diagnosis module includes a comparator for comparing the conductance matrix for the body part to an average conductance matrix from a population group to diagnose the possibility of disease in the body part.

24. The system of claim 22, wherein the diagnosis module includes a comparator for comparing the conductance matrix for the body part to a conductance matrix for a homologous body part to diagnose the possibility of disease in the body part.

25. The system of claim 22, wherein the admittance module includes

an auxiliary module for calculating an $N_e - 1 \times N_e - 1$ auxiliary matrix A with matrix elements a_{ij}, the auxiliary matrix given by

$$A = \left(Z^{-1} + \operatorname{adj} Z^{-1}\right)/2; \text{ and}$$

an admittance matrix calculator for calculating the admittance matrix Y, with matrix elements y_{ij}, according to

$$y_{ij} = \begin{cases} a_{ij} \text{ if } 1 \le i \le N_e - 1 \text{ and } 1 \le j \le N_e - 1 \\ x_i \text{ if } i = N_e \text{ or } j = N_e \\ -\sum_{n=1}^{N_e - 1} x_n \text{ if } i = N_e \text{ and } j = N_e \end{cases}$$

where

$$x_j = \sum_{n=1}^{N_e - 1} a_{ji}.$$

26. The system of claim 25, wherein the conductance module includes a conductance matrix calculator for solving the equation

$$G_{ee} - G_{ei} G_{ii}^{-1} G_{ei}^T = \mathrm{Re}(Y),$$

where, if N_e is the number of external nodes and N_i is the number of internal nodes, then G_{ee} is an $N_e \times N_e$ matrix, G_{ei} is an $N_e \times N_i$ matrix and G_{ii} is an $N_i \times N_i$ matrix defined by

$$G = \begin{pmatrix} G_{ee} & G_{ei} \\ G_{ei}^T & G_{ii} \end{pmatrix}.$$

27. The system of claim 26, wherein the conductance matrix calculator solves the equation

$$G_{ee} - G_{ei} G_{ii}^{-1} G_{ei}^T = \mathrm{Re}(Y)$$

by utilizing at least one of Newton's method for a system of nonlinear equations and a continuation method.

28. The system of claim 25, wherein the electrical data unit further includes an averaging module for calculating an average impedance matrix $\overline{Y}$, by averaging over one or more impedance matrices, including Y, obtained by varying the reference electrode chosen from among the plurality.

29. The system of claim 28, wherein the conductance module includes a conductance matrix calculator for solving the equation

$$G_{ee} - G_{ei}G_{ii}^{-1}G_{ei}^{T} = \mathrm{Re}(\overline{Y}),$$

where, if N_e is the number of external nodes and N_i is the number of internal nodes, then G_{ee} is an $N_e \times N_e$ matrix, G_{ei} is an $N_e \times N_i$ matrix and G_{ii} is an $N_i \times N_i$ matrix defined by

$$G = \begin{pmatrix} G_{ee} & G_{ei} \\ G_{ei}^{T} & G_{ii} \end{pmatrix}.$$

30. The system of claim 29, wherein the conductance matrix calculator solves the equation

$$G_{ee} - G_{ei}G_{ii}^{-1}G_{ei}^{T} = \mathrm{Re}(\overline{Y})$$

by utilizing at least one of Newton's method for a system of nonlinear equations and a continuation method.

31. The system of claim 17, wherein the current pathways intersect only at external nodes or internal nodes.

32. The system of claim 17, wherein the current pathways are line segments.

33. The system of claim 17, wherein the external nodes lie on a perimeter of the network and the internal nodes lie inside the perimeter.

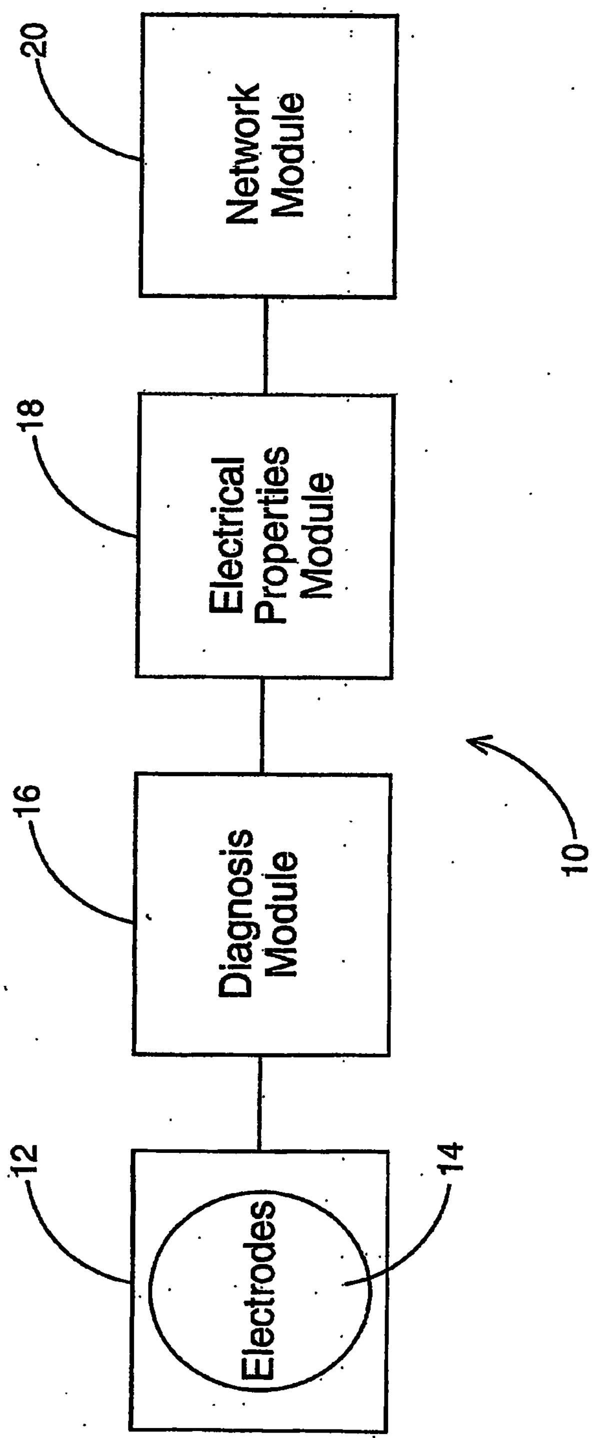
20
Network Module
18
Electrical Properties Module
16
Diagnosis Module
12
Electrodes
14
10

FIG. 1

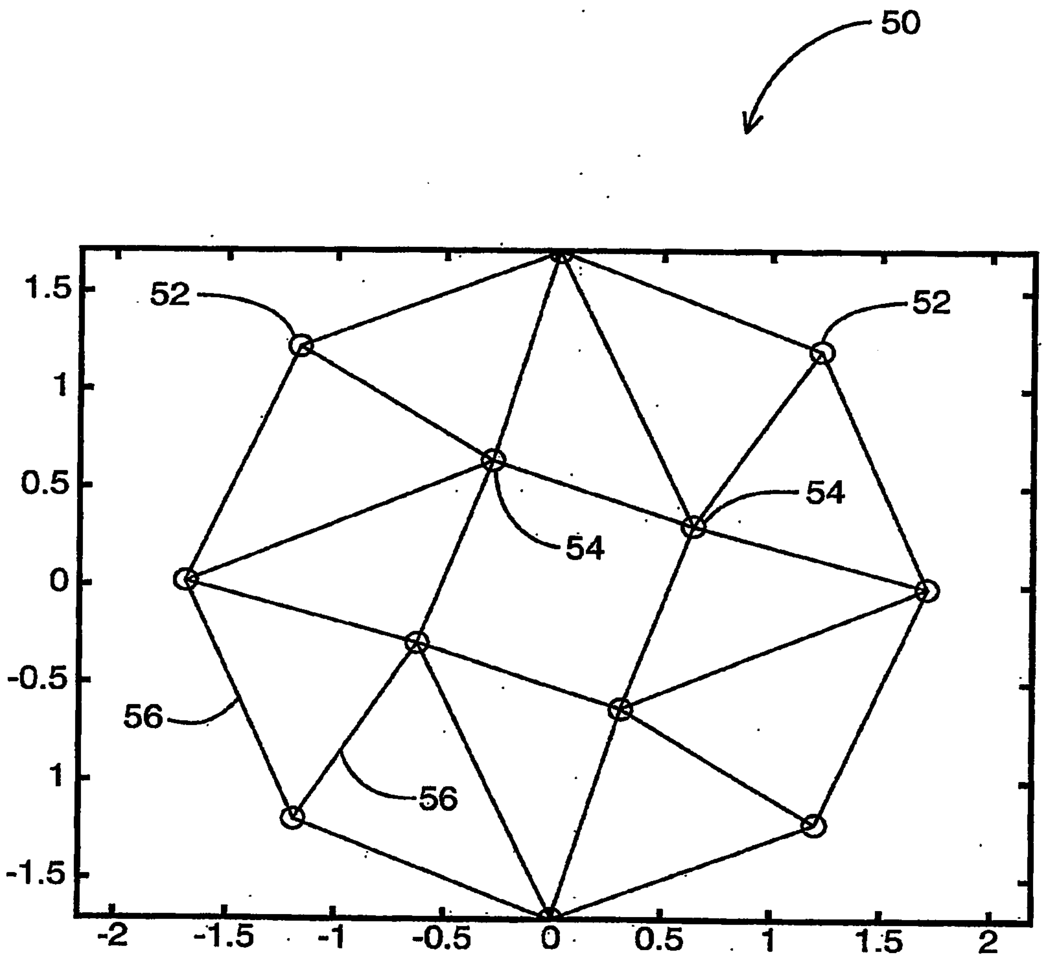

FIG. 2

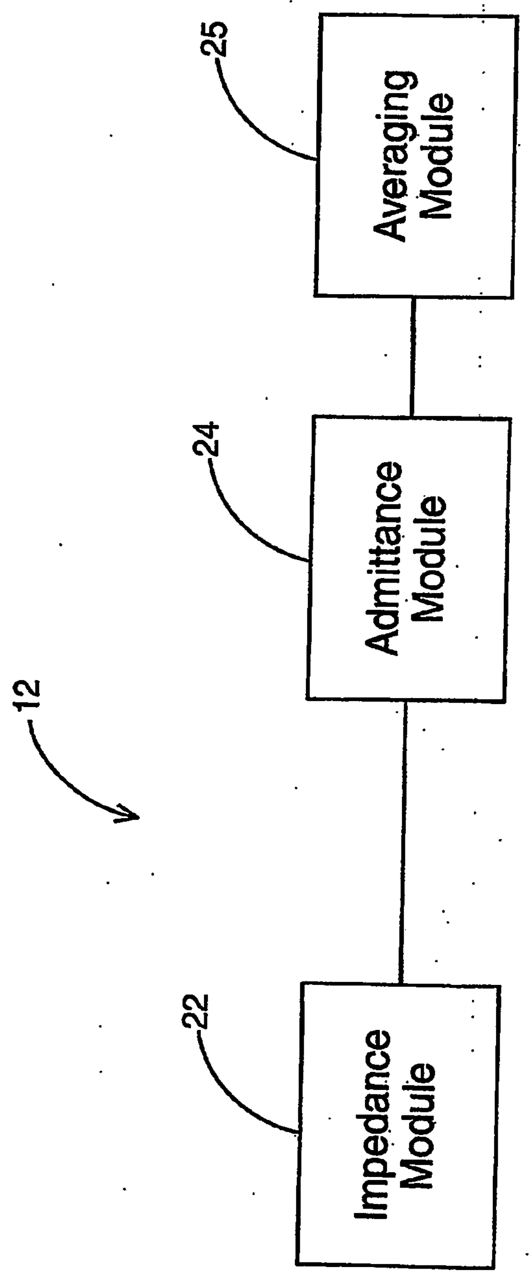
25
Averaging Module
24
Admittance Module
12
22
Impedance Module

FIG. 3

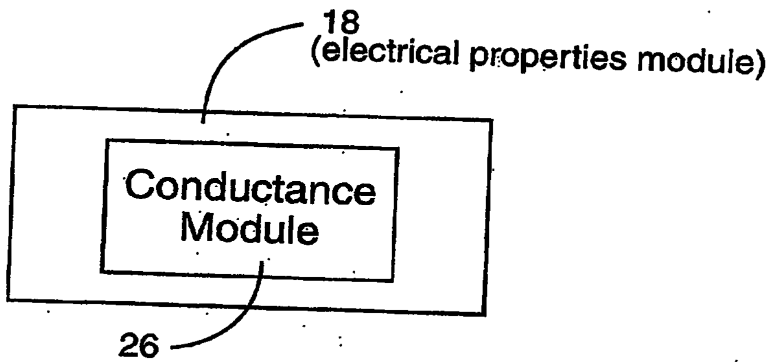
18
(electrical properties module)
Conductance Module
26

FIG. 4

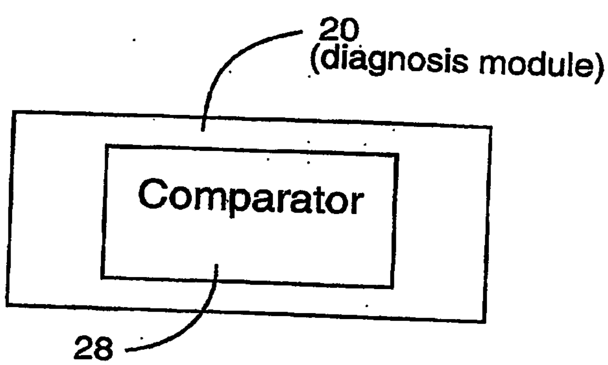
20
(diagnosis module)
Comparator
28

FIG. 5

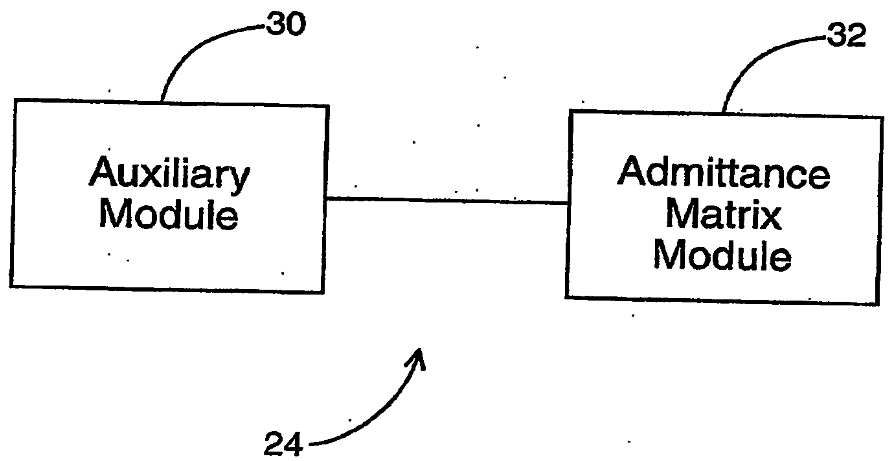
30
32
Auxiliary Module
Admittance Matrix Module
24

FIG. 6

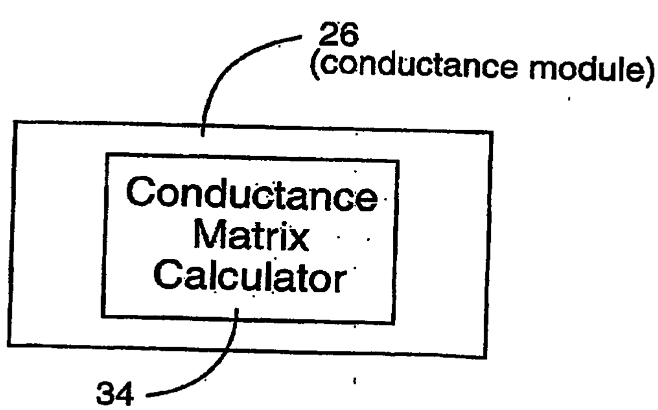
26
(conductance module)
Conductance Matrix Calculator
34

FIG. 7